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A WAVELENGTH MULTIPLEXED BIDIRECTIONAL FIBER RING NETWORK

by

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Specific wavelength channels are routed bi-directionally through the eight nodes, minimizing the number of hops a message must take to reach its destination. Information on multiple wavelengths propagates through the BADMs in both directions. Each BADM adds (drops) two wavelengths to (from) the ring network. The BADMs are constructed using thin film filters, an all-optical technology.

Because the number of optical/electrical/optical conversions were reduced in this network, the benefits of optical fiber can be better utilized in small-scale networks. Showing that local area networks can operate at high data rates in a single fiber ring, while maintaining scalability and modularity, would significantly enhance the possibility of installing smaller-scale optical fiber networks.

Keywords: WDM, Optical, Networks, Fiber Ring, ADM

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Introduction

Fiber optic networks are becoming more prevalent every day. In the average day, over 4000 miles of fiber strands are being installed. Users of fiber include companies that require a faster connection between offices, users of the internet, as well as consumers using long distance telephone services. The bulk of data transfer with other continents is done through fiber optic cables laid on the ocean floor (the most well-known being the transatlantic fiber cable connecting North America and Europe). [1]

The switch to fiber optic cable over the past 20 years from other technologies, such as copper wire, radio, or free space communication, is due to some key advantages. For one, optical fiber has an enormous bandwidth (over 10 THz). This allows the transmission of many frequency channels over the same fiber, possibly with different data formats on each channel. A second advantage is that fiber optic lines have much less power loss over a long distance than copper. The fiber itself is also inexpensive, costing a few cents per kilometer, though optical amplifiers, lasers and components required in optical networks are often expensive.

Optical fiber technology has some appealing advantages for the Navy. Imagine a single local area network on a destroyer that transfers fire control data and navigation information, as well as outgoing email, sending them to their destinations almost instantaneously. This can be done easily in an optical fiber. Other advantages include scalability, the ability to add nodes into the network as required, and the ability to prioritize data, so that the most important data, such as fire control data, gets through securely. It is possible that secure and reliable communication on an entire ship could be done using one network that operates across a single fiber ring. Faults

could be tolerated by adding redundancy, possibly with multiple fiber rings or with multiple wavelengths.

In this project, the physical layer of such a fiber ring network was built and tested. The network relies on a device called a bidirectional add-drop multiplexer (BADM). A BADM is an optical component that allows information on multiple wavelength channels to pass through in either direction while dropping or adding information on other wavelength channels. Because the BADM is bidirectional, the network can transmit information in both directions around the fiber ring. After the BADM was integrated into the network and the fiber ring was constructed, flexibility and capacity was tested by transmitting different signal formats with digital and analog information, at variable data rates or carrier frequencies. As of now, fiber is most widely used in long distance trunks and network backbones. This project shows that a fiber ring network that includes the use of BADMs can harness the advantages of optical fiber in local area networks (LAN) as well.

Background

Optical waves propagate in glass fiber because of a difference in the index of refraction in the center core and the surrounding cladding as shown in Figure 1, where n_1 is the core refractive index, and n_2 is the cladding index. When a propagating wave is incident on the core-

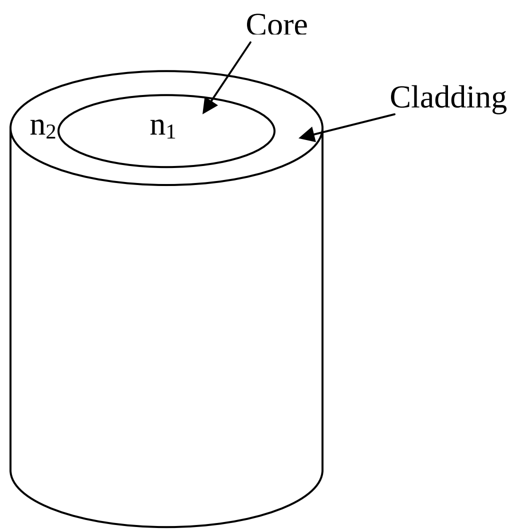


Figure 1: Optical fiber cross-section.

cladding interface, there can be a reflected wave, as well as a refracted wave that enters the new medium. The wave propagation at the interface between the core and cladding is described by Snell's Law:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \tag{1}$$

where θ_1 is the angle of the incident wave in the core, and θ_2 is the angle of the refracted wave in the cladding, as shown in Figure 2.

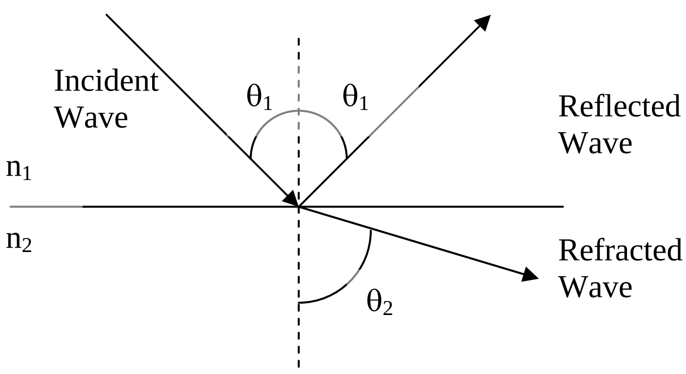


Figure 2: Snell's Law at an interface between two media.

Since $n_1 > n_2$ in the fiber, as θ_1 increases, θ_2 approaches 90°, at which point, all of the incident energy is reflected. Under these circumstances, the incident wave propagates at a shallow enough angle that none of the energy from the incident wave enters into the cladding. This condition is called total internal reflection, and it occurs when $\theta_2 = 90°$, such that

$$\theta_1 = \theta_c = \sin^{-1} (n_2/n_1). \quad (2)$$

The angle θ_c is referred to as the critical angle. In standard single mode fiber with $n_1 \approx 1.45$ and $n_2 \approx 1.435$, the critical angle, $\theta_c \approx 81.75°$. Thus, most of the light propagates approximately straight down the fiber.

In a fiber network, information is transferred between multiple locations. There are three common methods of distinguishing signals from one another and routing them between these locations. The first is called spatial division multiplexing (SDM). SDM uses multiple fibers for different connections. In a simple example, one fiber could be used to send email to first wing from main office, and a second fiber could be used to send email to second wing. In this case, expanding a network simply requires more fibers. However, if each new fiber needs its own amplifiers or repeaters, this can be expensive and complicated as the network size increases. Accordingly, SDM is a strategy that does not scale well.

Alternative strategies use fewer fibers to implement the network. To send multiple streams, or channels, of information over the same fiber, networks must use multiplexers (MUX) and demultiplexers (DEMUX) to combine and separate the streams, respectively. These devices multiplex the information in either time or optical frequency. With time-division multiplexing (TDM) different time slots are used for different channels. Generally, digital information is carried in binary digits, or bits. If each TDM stream has the same data rate in bits/sec, the aggregate data rate required to transmit all the data is N times faster than the data rate on each

stream (if N streams are multiplexed). The multiplexer can do one of two things: it can either transmit the bits from each input stream immediately, or it can transmit a packet of (multiple) bits from one stream followed by a packet from the next stream and so on. TDM is a strategy that can take advantage of already installed fiber infrastructures. As a result, TDM makes a larger-scale network more practical and affordable. However, the aggregate throughput is limited by the maximum data that can be achieved on a given frequency channel. Currently, transmission rates for a single TDM channel often operate as high as 10 Gb/s, though systems operating at 40 Gb/s are now commercially available. TDM is the traditional method of multiplexing information onto transmission media.

Possibly the fastest growing method for transferring multiple data streams is called wave division multiplexing (WDM), in which different frequency channels co-propagate down the same fiber. Multiplexed and demultiplexed WDM streams can remain optical, which is an advantage since the data rate is usually limited by the speed at which the conversion between the optical format and the electrical format can occur. To appreciate the advantage of WDM, consider the network in Figure 3.

If this were an SDM network, the eight nodes would be connected using sixteen fibers, one for each connection between the nodes. The light on every fiber would likely have the same frequency or wavelength. Each node effectively acts as a relay station. A message from a given node can eventually reach any other node depending on how the information is routed. For example, a message from Node 0 to Node 1 could be directly transmitted between them, or it could be transferred through Nodes 7 and 6 before reaching Node 1 if the direct link was

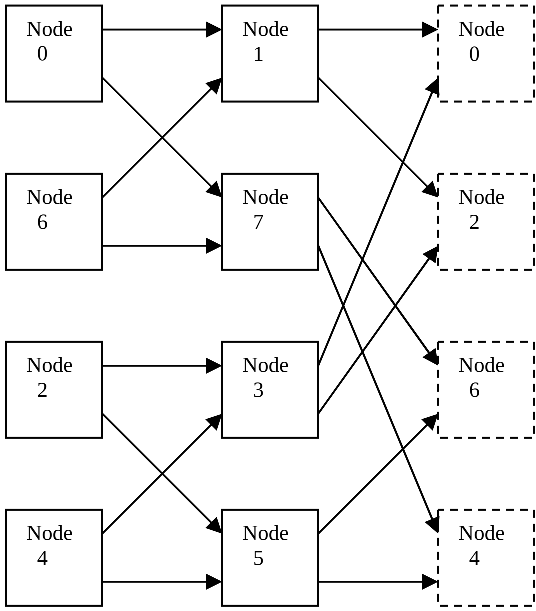


Figure 3: Interconnection graph for an eight-node perfect shuffle network.

unavailable for some reason. The network topology shown in Figure 3 is known as a perfect shuffle. A perfect shuffle is used to minimize the diameter of the network (the maximum number of hops transmitted data must take to reach its destination), which is three for the network in Figure 1 (for example, Node 0 sending data to Node 3). Also, the number of hops required to reach a destination can be an architectural tool. For instance, information can be prioritized by configuring the network so that certain data only needs one hop to reach its destination instead of three. Thus, the information arrives faster. These are some of the advantages characteristic of perfect shuffle topologies.

Now, suppose instead that each connection in Figure 3 occurred on a specific optical frequency. Each node then serves as a relay station that translates the information between different optical wavelengths. Routing information could be contained within the signal itself. The physical topology for such a WDM network could use a single fiber ring and four optical

wavelengths, as shown in Figure 4. Each node requires two transmitters (Tx) and receivers (Rx), each operating at different optical frequencies as shown. Optical frequency f_i is related to wavelength λ_i using the equation

$$f_i = c / \lambda_i \tag{3}$$

where c is the constant for the speed of light in free space, 3 x 10^8 m/s. This is the network that was simulated, built, and tested in this project. Careful analysis of Figure 4 shows that the connections are identical to those in Figure 3. The colors labeled for each channel do not correspond to the actual color of the light in each channel. Light near 1550 nm is in the near infrared region of the electromagnetic spectrum and is invisible to the eye.

One important aspect of this project involves the bidirectional add-drop multiplexer, labeled as BADM in Figure 4. ADMs (non-bidirectional) are used in many different ways in optical networks. In this network, the BADM separates multiple wavelength channels that propagate in a bidirectional manner around the ring, dropping two wavelength channels from the

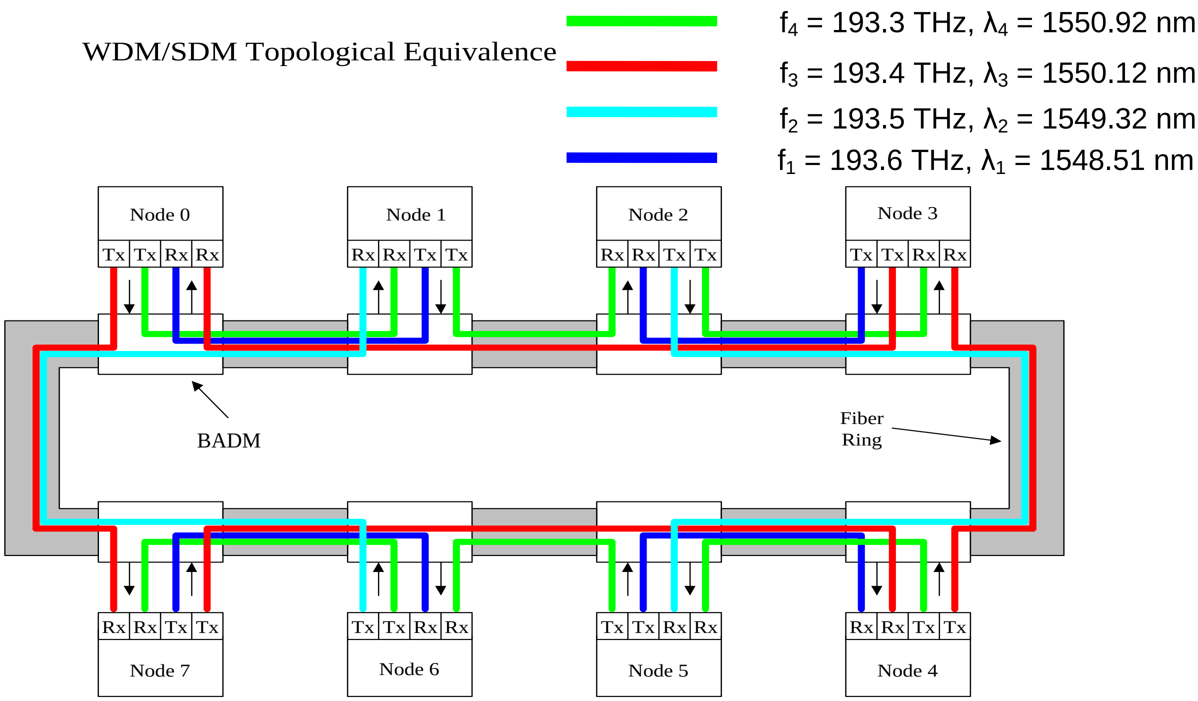


Figure 4: Topological equivalent eight-node fiber ring network using WDM and bidirectional data flow.

ring, while also adding two wavelength channels. For example, the BADM for Node 0 drops the dark blue and red channels that propagate around the fiber ring towards the node in a counter-clockwise manner, whereas the added wavelengths propagate in opposite direction from one another. Specifically, the red wavelength is added back into the ring in the counter-clockwise direction, and the green wavelength is added in the clockwise direction.

The network in Figure 4 was analyzed in several ways. First, the network was constructed using eight BADMs that were custom designed and built by JDS Uniphase. Multiple data types were transmitted through the network at speeds as high 2.5 Gb/s, and the performance of the network was evaluated. To test the network at higher data rates, numerical modeling was used. In addition to testing, an analysis was done on how the eight-node network would integrate into larger real-world networks. The analysis verified the practicality of the project.

The Add-Drop Multiplexer

The most unique and new feature of the eight-node network and the project is the role of the BADM in Figure 4. The network structure is impossible to implement without this device. Its novelty lies in its bidirectional function and in its capability to add and drop multiple frequencies. Before analyzing this device, it is best to develop an understanding of existing ADMs and their function in networks today.

Add-drop multiplexers (ADMs) are very common in networks and are commercially available from many vendors. Depending on their application, they can be rather complex or quite simple in their functionality. A simple ADM is usually unidirectional, meaning that it can only add and drop frequencies (or information channels) that carry data in a single direction in the fiber. Additionally, it usually adds and drops only a single frequency. The function of a

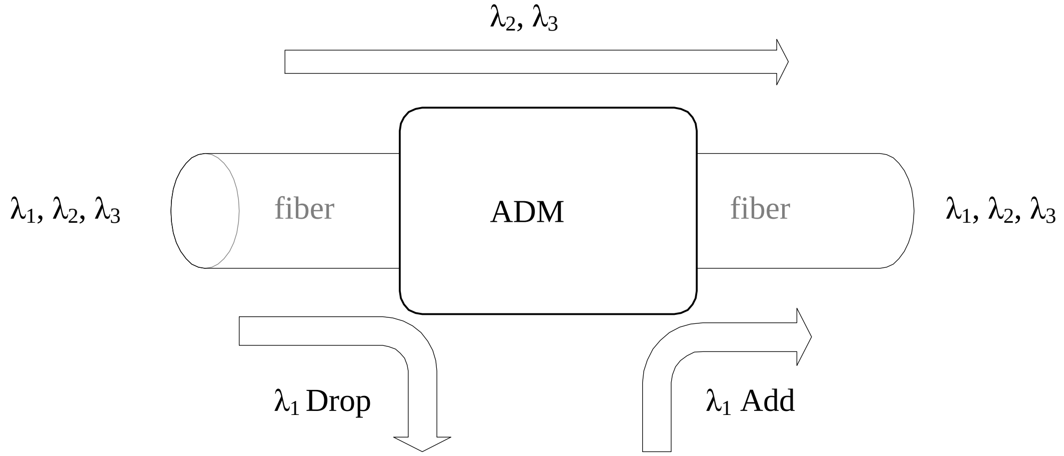


Figure 5: A typical unidirectional one wavelength ADM.

simple ADM is illustrated in Figure 5. Three WDM channels are input from the left, each of which travels on a different wavelength. The ADM separates (or drops) one wavelength, λ_1, from the others, and then adds it back to the stream (with new data) at the output on the right.

While there are a variety of ways to build an ADM, two different techniques will be discussed here. Both use passive optical components that require no external power source to control their operation.

One common ADM uses circulators and fiber Bragg gratings. The circulator, as illustrated in Figure 6 is a three-port device. An optical wave entering at one port propagates around the loop and exits at the next port. Examples are illustrated in color for each of the three ports. These demonstrate all of the possible input and output combinations for the three ports.

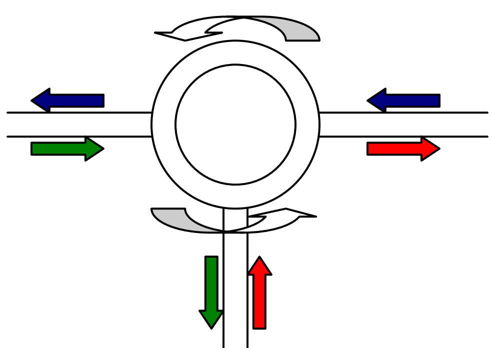


Figure 6: Three-port circulator

The second component used in this type of ADM is called a fiber Bragg grating (FBG). In an FBG, the index of refraction varies periodically along the length of the fiber. The period of the variation in the index defines the wavelength of light that will be reflected from the grating. Other wavelengths pass through the grating without reflection [1].

Figure 7 displays the reflectivity of a typical grating as a function of the wavelength, relative to the central wavelength. The graph shows that for the central wavelength, an FBG can reflect close to 100% of the power. For channels 0.8 nm away from that wavelength, this FBG is transmissive, allowing the power to pass through without being reflected. The characteristic center wavelength of the reflected light is given by

$$\lambda = 2n_{\mathbf{eff}}\,\Lambda, \tag{4}$$

where Λ is the period of the variation in the index of refraction and n_{eff} is the effective index of refraction of the grating. The parameter, λ, is sometimes referred to as the Bragg wavelength.

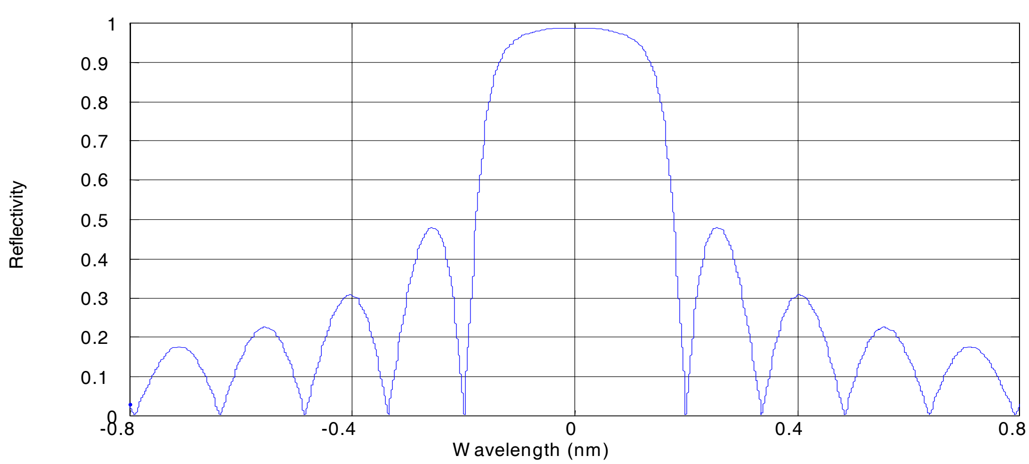


Figure 7: Reflectivity versus wavelength for an FBG.

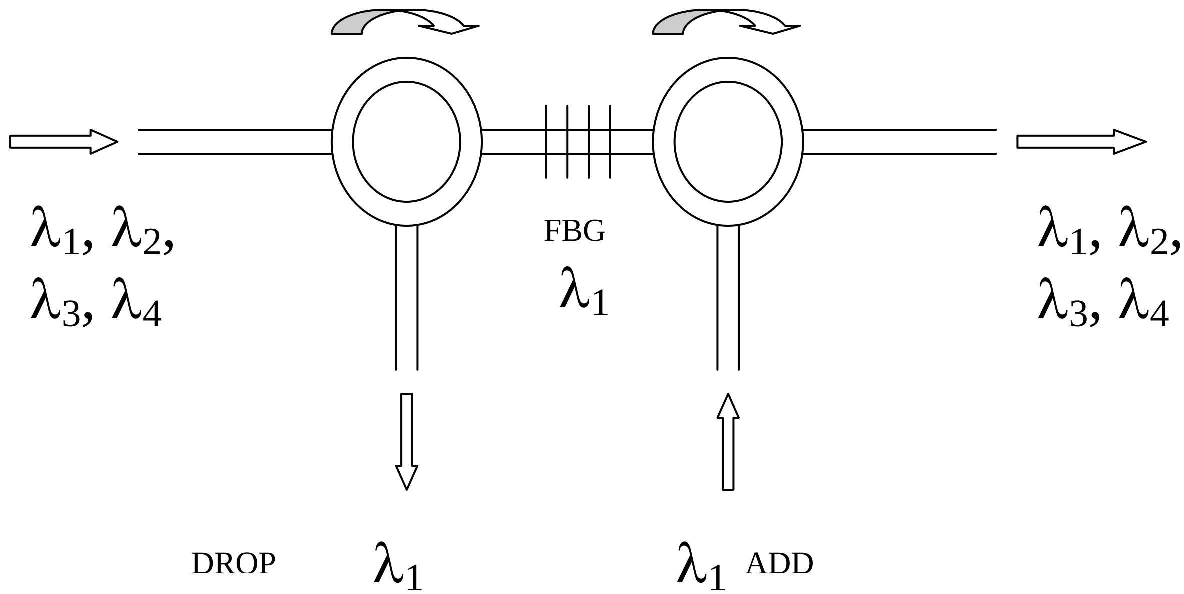


Figure 8: A typical one-wavelength ADM using circulators and an FBG.

The design of a common ADM using circulators and an FBG is shown in Figure 8. This design uses two circulators and one FBG. λ_1 travels a different path than the other wavelengths because the FBG located between the two circulators is designed to reflect λ_1 while transmitting all other frequencies. The dropped channel, λ_1, approaches the FBG from the left, along with wavelengths, $\lambda_2 - \lambda_4$. The FBG reflects λ_1 back towards the first circulator, where the channel exits the ADM at the bottom of the figure. Similarly, the added channel, λ_1, enters the ADM from the bottom right of the figure, propagates toward the FBG from the right, where it is reflected back towards the output on the right, along with the other wavelengths. Because the FBG reflects the dropped and added channel in opposite directions, dropped information stays separate from the added information.

ADMs can also be built using thin film filter technology. The principle of operation of a thin film filter is related to the frequency-dependent reflection and refraction of an optical signal at a periodic interface between materials with two different indices of refraction. As light is

reflected and refracted from the periodic structure (based on Snell's Law) the frequency of the reflected light may be different than that of the refracted light. In a thin film filter, the refracted, or transmitted, light is composed of a narrow band of frequencies around a characteristic frequency. This central frequency depends on the thickness of the thin films that make up the periodic structure. Frequencies outside of this band are mostly reflected. The technique is displayed in Figure 9. In this figure, the resonant wavelength is shown next to each filter. This is the wavelength that is transmitted by each filter. A thin film filter can add or drop the wavelength, as illustrated in Figure 9 for wavelength channel, λ_1. Channels on λ_2 and λ_3 are reflected by each device. The resulting device functions as a unidirectional, single wavelength ADM [1].

Using the ADM designs described, there are a number of ways that multiple nodes can be connected in a network. However, the limited capabilities of such ADMs either require a more complicated fiber infrastructure than a simple ring (as in Figure 4) or do not make efficient use of available WDM channels. In both cases, performance is limited by the simple functionality of a typical ADM.

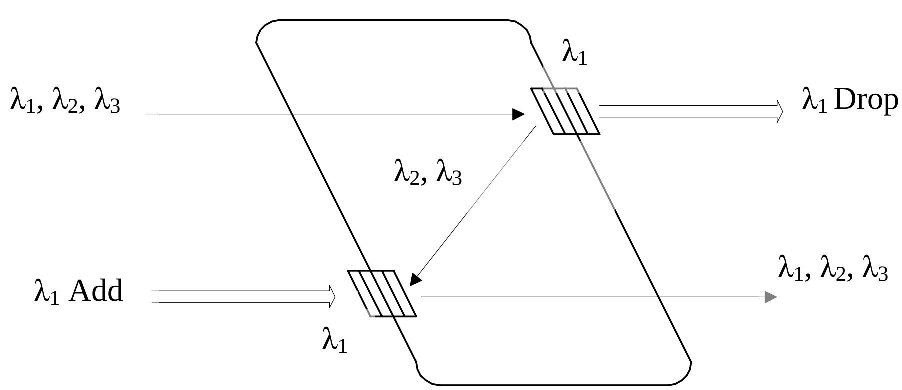


Figure 9: ADM design using two thin film filters.

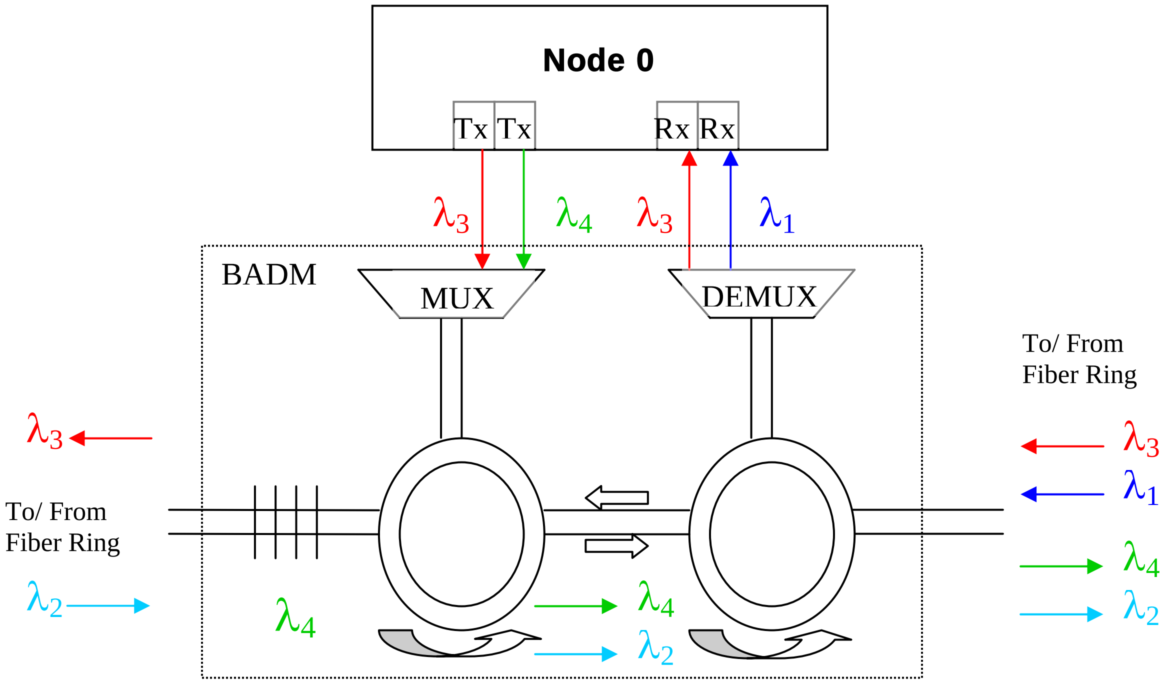


Figure 10: Design for a bi-directional, multi-wavelength ADM.

Figure 4 demonstrates how an ADM with bidirectional capability that adds (drops) multiple wavelengths could make the implementation of more complicated networks possible while using a simple fiber infrastructure. Figure 10 shows a circulator/FBG implementation of such a device. Though it also uses one FBG and two circulators, it allows for bidirectional signal propagation and can add and drop multiple wavelengths. The BADM in Figure 10 functions as Node 0 of Figure 4. A wavelength multiplexer and demultiplexer is also used in Figure 10 to combine and separate signals of different wavelengths onto the same fiber. Figure 11 shows the same BADM device for Node 0, but constructed using thin film filters.

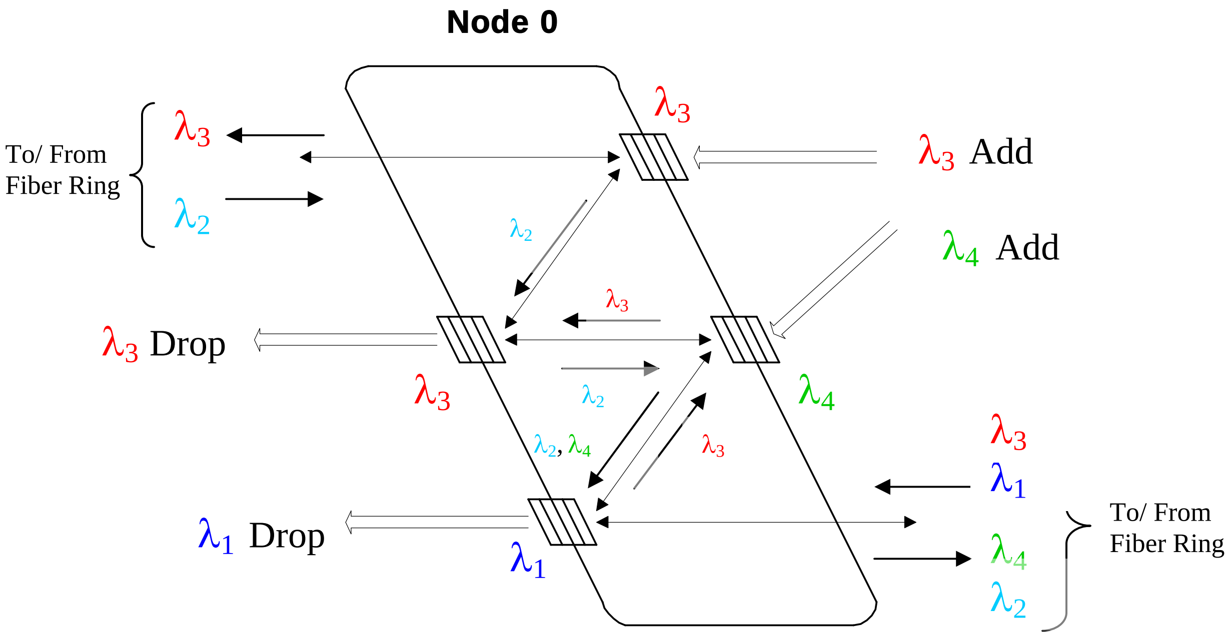


Figure 11: Design for a bi-directional, multi-wavelength ADM.

For this project, the thin film filter-based BADM in Figure 11 was custom designed and manufactured by JDS Uniphase Corporation. It has some significant advantages over the device in Figure 10. The first advantage is flexibility. In a thin film filter BADM, a drop channel can be configured as an add channel and vice versa. The λ_1 channel in Figure 12 demonstrates this concept. A second advantage is cost. The device in Figure 11 is only slightly more expensive than a single four-wavelength multiplexer, and considerably less expensive than the device implemented with circulators and FBGs. With eight of the thin film filter BADMs, the entire eight-node network topology from Figure 3 was implemented in a single fiber ring as in Figure 4. High speed digital data, as well as analog data, was successfully transmitted through the network, as described in the next section.

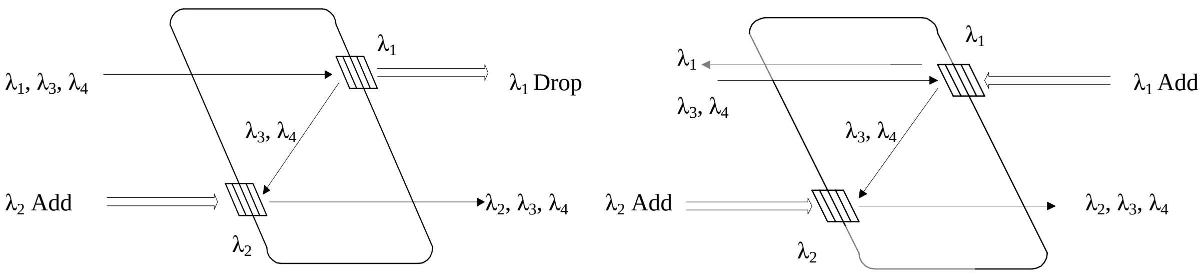


Fig. 12. λ_1 channel used either as a Drop (left) or as an Add (right).

Experimental Results

Figure 13 shows the initial setup used to test the eight-node network, with the locations of the different lasers, all tuned to a different frequency, as shown. Before connecting the BADMs to form the eight-node network, the BADM channels were individually tested for functionality. To confirm that each device added or dropped the correct frequencies, the transfer function of each channel was measured using a tunable laser source. These transfer functions, which define the spectral response of the device, were later used in computer simulation as well.

The test setup in Figure 13 utilizes four laser transmitters. The optical signals coming from the lasers were initially not modulated with data. After propagating through the network, each signal was received at either Node 0 or Node 1. A multiplexer (MUX) was used to combine the separate wavelength channels for viewing on an optical spectrum analyzer (OSA).

Note the presence of every channel within the fiber segment between the BADMs at Node 0 and Node 1. In this arrangement, the maximum degree of interference or crosstalk

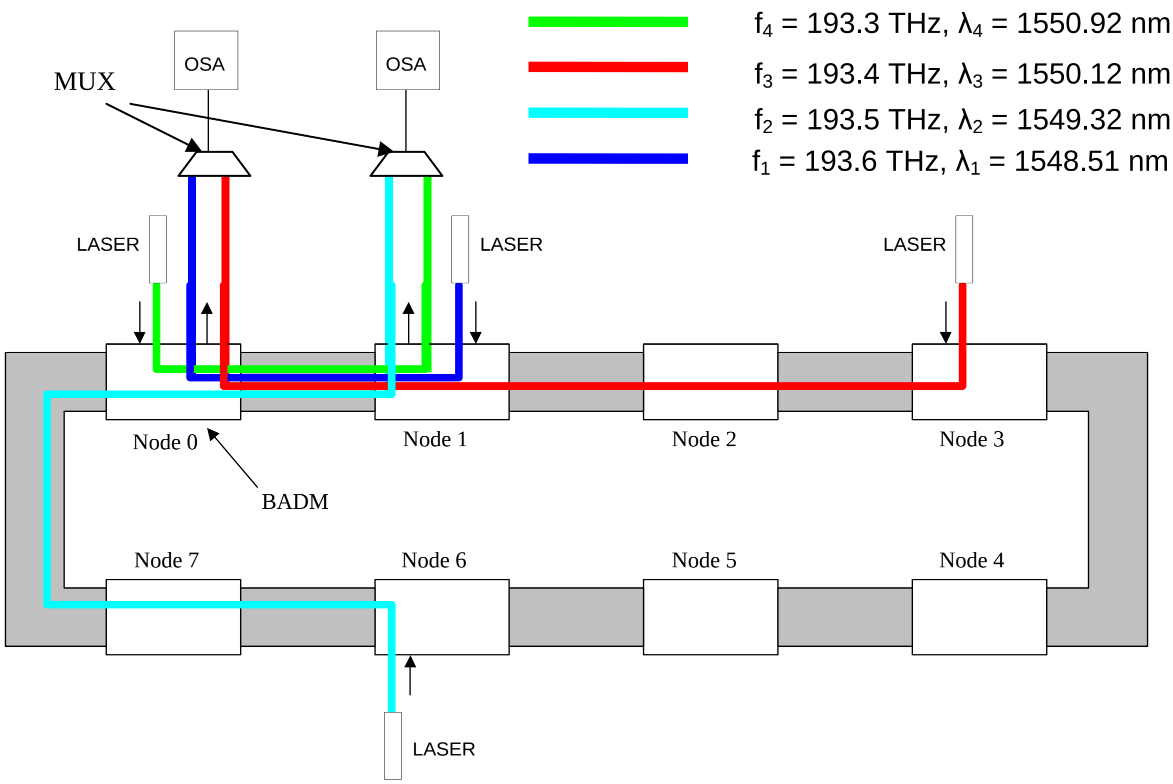


Figure 13: Initial setup for testing eight-node network.

between channels can result and would be observed on the OSA if any problems were to occur. In addition, channels λ_2 and λ_3 propagate over the longest path possible in the network, so that the impact of attenuation can be ascertained.

This test, despite only including a fraction of the network, indicates how the entire network might function with data transmitted on every channel. The resulting OSA graphs prove that the BADMs in Node 0 and Node 1 operate properly. The correct signals were received at both nodes as illustrated by the OSA output shown in Figure 14.

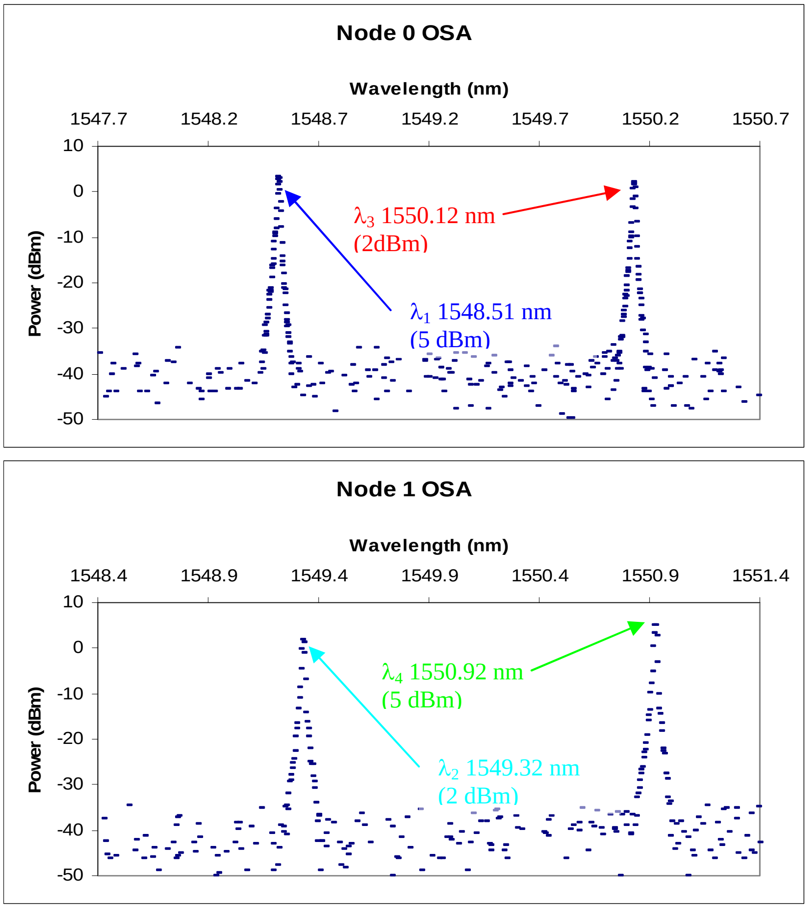


Figure 14: OSA graphs for received signals at Node 0 and Node 1 in four-node network.

The peaks in power in these two graphs are as expected. Node 0 receives channels λ_1 and λ_3 (on 1548.51 nm and 1550.12 nm, respectively), and Node 1 receives channels λ_2 and λ_4 (on 1549.32 nm and 1550.92 nm). Though it is slight, there are small differences in power between the channels. Channels λ_1 and λ_4 have 5 dBm power, while the power levels in channels λ_2 and λ_3 are about 2 dBm. This is as expected, based on the insertion losses of the BADMs as specified by the manufacturer. Though all lasers are transmitting at a constant power (6 dBm specifically), the signal paths are different for each channel. Channels λ_1 and λ_4 each travel through two BADMs, while channels λ_2 and λ_3 travel through four. Hence, there is 3 dB more power in λ_1 and λ_4 at the

receiver. Given the magnitude of the resulting power levels, though, there will be little impact on the clarity of information that will be received since the signal-to-noise ratios approach 50 dB in Figure 14.

Once the basic operation of the network was demonstrated with just a few nodes, more extensive testing was then appropriate. Figure 15 shows a picture of the test setup. Key testing devices are labeled. The laser transmitter box contains five lasers that emit light at different frequencies. The outputs are modulated with the analog or digital data to be transmitted. The optical signals then enter the network through a port in a BADM. Of the eight BADMs shown in Figure 15, only the BADM for Node 2 is labeled. Two 25 km fiber spools were added between Node 3 and Node 4 to assess the performance constraints of the network, though such lengths would be atypical of a LAN. After traversing the network, the channels are output to an optical receiver, which converts the optical signal into an electrical signal. The electrical signal

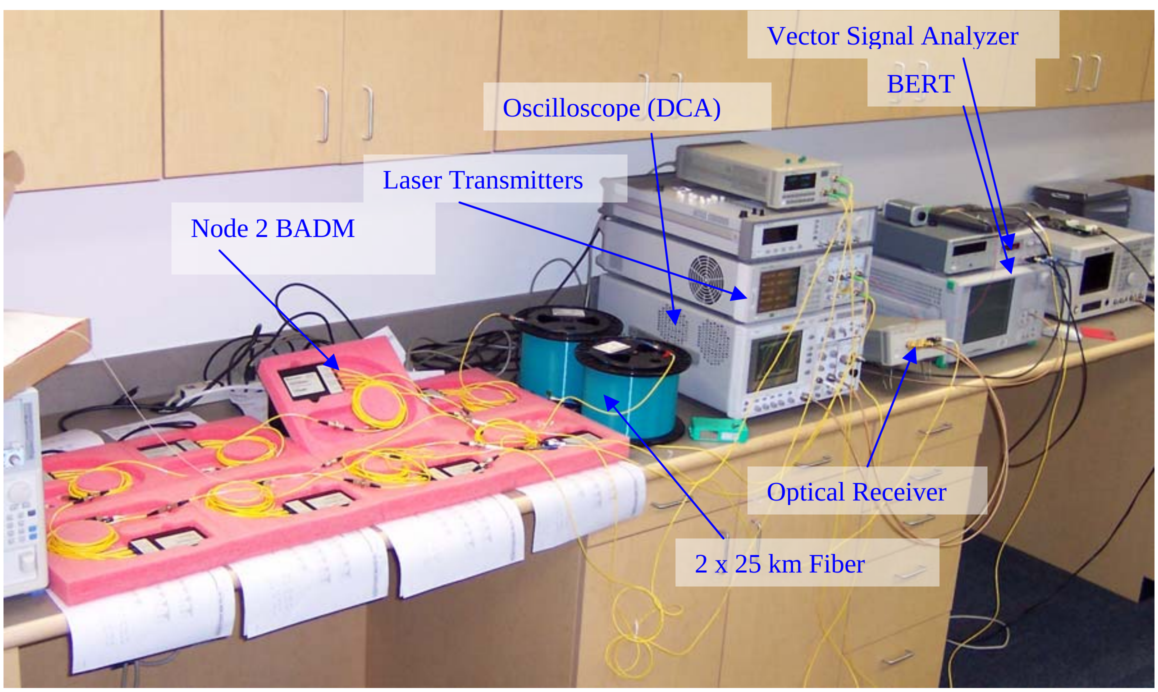


Figure 15: Picture of laboratory setup.

from the receiver then drives the bit error rate tester (BERT) or the high speed oscilloscope, also referred to as a digital communications analyzer (DCA).

The purpose of testing the eight node network after verifying its operation is to realize the capabilities of the network. Performance was established using signal clarity as an indicator. With digital signals, clarity is measured by the bit error rate (BER). The BER defines the number of bits that are in error divided by the total number of bits received. 10^{-9} is a standard value defined as error-free performance. Anything less than that is considered adequate for network performance. Analog signals use signal to noise ratios (SNR) to measure performance. SNR is the ratio in received power between the signal and the noise. To test the network performance in the eight node network, the setup in Figure 16 was used.

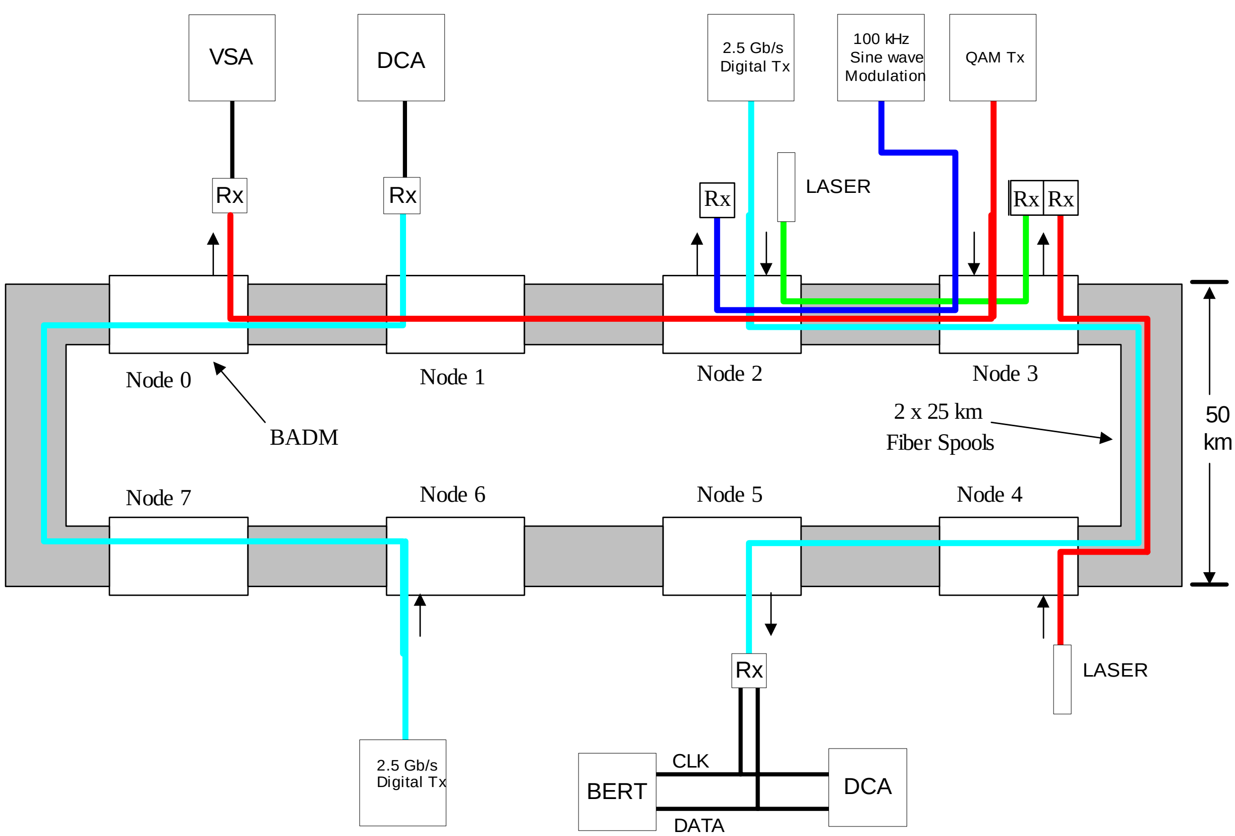


Figure 16: Laboratory setup used in testing the performance of the network.

Figure 16 shows that several different types of signals were used simultaneously to test the network. Digital data was transmitted (Tx) through the network on the λ_2 channel (light blue) at 193.5 THz. An optical modulator was used to externally modulate the laser output at a 2.5 Gb/s data rate. Optical modulators have two inputs: an unmodulated continuous wave optical signal and an electrical input. The electrical signal contains data that modulates the optical signal. The electrical data signal is created in a digital pattern generator in the BERT. At the receiver, the BERT then compares the received (Rx) data to the original transmitted pattern to determine the BER. The 193.5 THz channel that enters the network at Node 2 transmits at roughly 0 dBm (1mW) of optical power and propagates through 50 km of fiber before it is output at Node 5. The received optical power at Node 5 was approximately -13 dBm (50 µW).

An eye diagram is generated from a digital data stream by triggering on every bit in the stream. The result is a diagram that graphs every possible set of transitions (from 0 to 0, 1 to 1, 0 to 1, and 1 to 0), overlaying them on the same graph. The degradation of a digital signal, consequently, is determined by the degree to which the resulting “eye” is closed. Figure 17 displays the eye diagram of the 193.5 THz channel received by Node 5 after it has propagated through two BADMs and 50 km of optical fiber. The optical receiver at Node 5 converts the optical signal to an electrical signal. The electrical signal is then received at the DCA. Signal integrity can be assessed with the DCA by using the eye diagram. The eye diagram in Figure 17 is relatively open, meaning there are likely few errors in the received stream. For the eye in Figure 17, no errors were produced in three entire days. This corresponds to a BER below 10^{-14}.

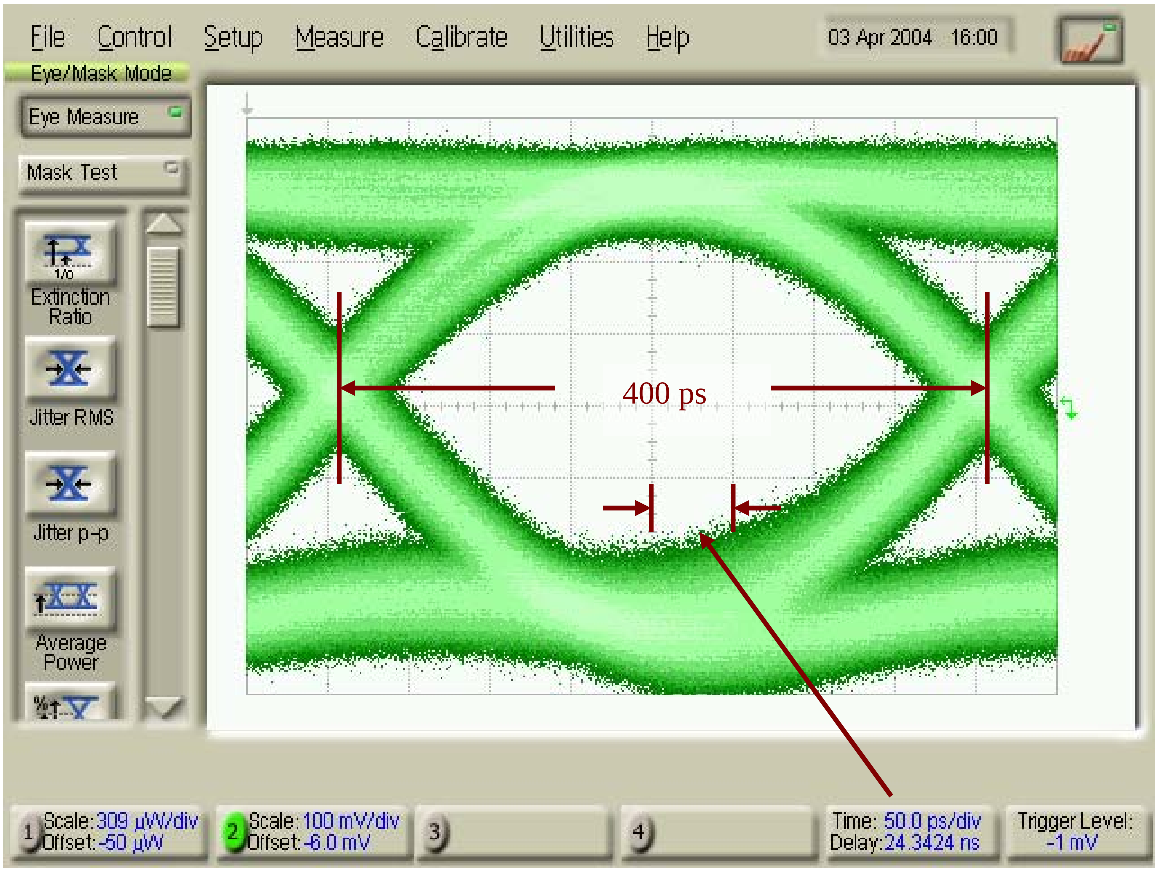


Figure 17: Eye diagram of 193.5 THz channel received at Node 5.

In fact, the channel did not produce errors consistently until the transmitted signal was attenuated by an additional 12 dB. Even with this much attenuation, the BER stayed below 10^{-9}. An additional loss of 12 dB corresponds to approximately 50 km of additional fiber (neglecting dispersion). Hence, the receiver sensitivity for a 10^{-9} BER was around -25 dBm (3 µW).

The second data format used to test the network was quadrature-amplitude modulation (QAM). A QAM signal uses symbols instead of bits to encode the data. These symbols are analog in nature and differ based on amplitude and phase. Because the signal is analog, QAM performance is measured by the SNR. Because a QAM signal uses multiple, discrete amplitude levels and phase values, the SNR requirements are more stringent than for simple analog modulation. In this test, a 16-QAM signal was generated that used four discrete amplitude states

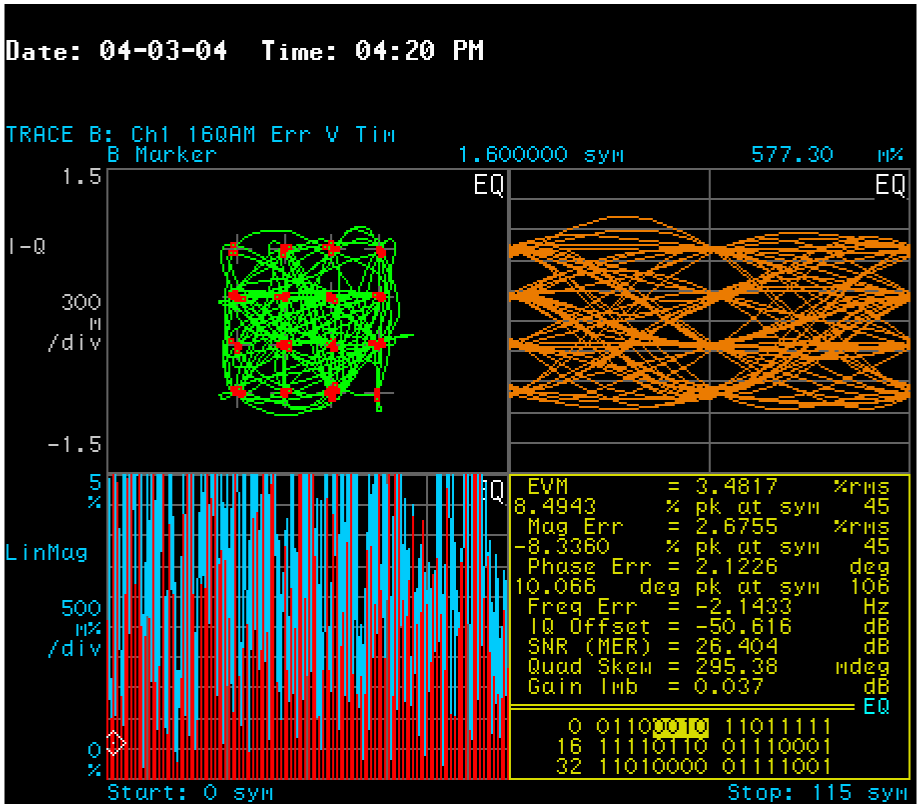


Figure 18: Received QAM signal performance

and two phase states, resulting in $4^2 = 16$ possible symbols. The vector signal analyzer (VSA), as depicted in Figure 16, is used to analyze a QAM signal after it is received. The QAM signal in this network is transmitted at Node 3 and received at Node 0 on the 193.4 THz channel, λ_3. Figure 18 displays four plots that depict the quality of the signal after it has been received. The upper left screen is a 16-QAM constellation plot. The red dots represent the 16 symbols of the QAM signal and are plotted at locations that correspond to their respective combination of amplitude and phase. The symbols are well separated from one another, indicating good performance. The second plot (upper right) is an eye diagram for one phase of the QAM signal. Four discrete amplitude levels are clearly observed. The overall performance of the QAM signal is determined by analyzing these top two plots. The SNR of the QAM signal, as measured by the VSA, is 26.404 dB (seen in lower right screen). This value increased to 28 dB as the equalization

of the VSA improved over time. The presence of the network changed the SNR by less than 1 dB, so there is little degradation of the signal in the ring network, itself. In other words, any degradation of the QAM signal occurs either at the transmitter or the receiver.

The digital signal between Nodes 2 and 5 and the QAM signal between Nodes 3 and 0 were simultaneously propagating through the network with four other channels. On two of them, the 193.3 THz (green) channel between Nodes 2 and 3 and the 193.4 THz (red) channel between Nodes 4 and 3, the optical signal was simply continuous wave (CW) light (no data was being transmitted). The third signal was another 2.5 Gb/s digital channel between Nodes 6 and 1 on 193.5 THz (light blue). The BER of this channel was also less than 10^{-9}, though it was attenuated 10 dB before entering the network. The last signal was transmitted on a 193.6 THz channel (dark blue) between Nodes 3 and 2. It was simply an analog optical signal modulated by a 100 kHz sine wave. This channel was simply included as yet another data format. Given the excellent performance on all the tests, any interference between channels was negligible, and the results demonstrate the robustness of the fiber ring network.

Computer Simulation

VPITransmissionMaker, made by Virtual Photonics Inc., is the computer program used to simulate the physical layer of an optical network. A multitude of various devices are included in the program to model the optical transmission layer of a network. A number of different types of laser and optical modulators are used to simulate optical transmitters. The program can model propagation of light in various kinds of fibers. Loss, dispersion, and fiber nonlinearity can be independently controlled to assess their importance in a given system design. Other modules in the program are used to model optical amplifiers, optical attenuators, polarizers, wave-division

multiplexers, and various optical receivers. VPITransmissionMaker uses visualizers to observe the results of the simulation. Optical and RF spectrum analyzers display the optical or electrical frequency content of a signal, respectively. Oscilloscopes show the signals in the time domain and can depict eye diagrams as well as calculate the bit error rate. Other visualizers are also available so that a signal may be analyzed in a variety of ways.

Computer simulation allowed for a more extensive analysis of the performance in the eight-node network. The actual network tested in the lab included two 2.5 Gb/s digital channels, one analog signal, and one QAM signal simultaneously. For the computer simulation, the digital transmission was extended to all 16 channels in the system, at data rates of 2.5 Gb/s and 10 Gb/s.

In Figure 19, the network in Figure 4 is modeled using a variety of different simulation

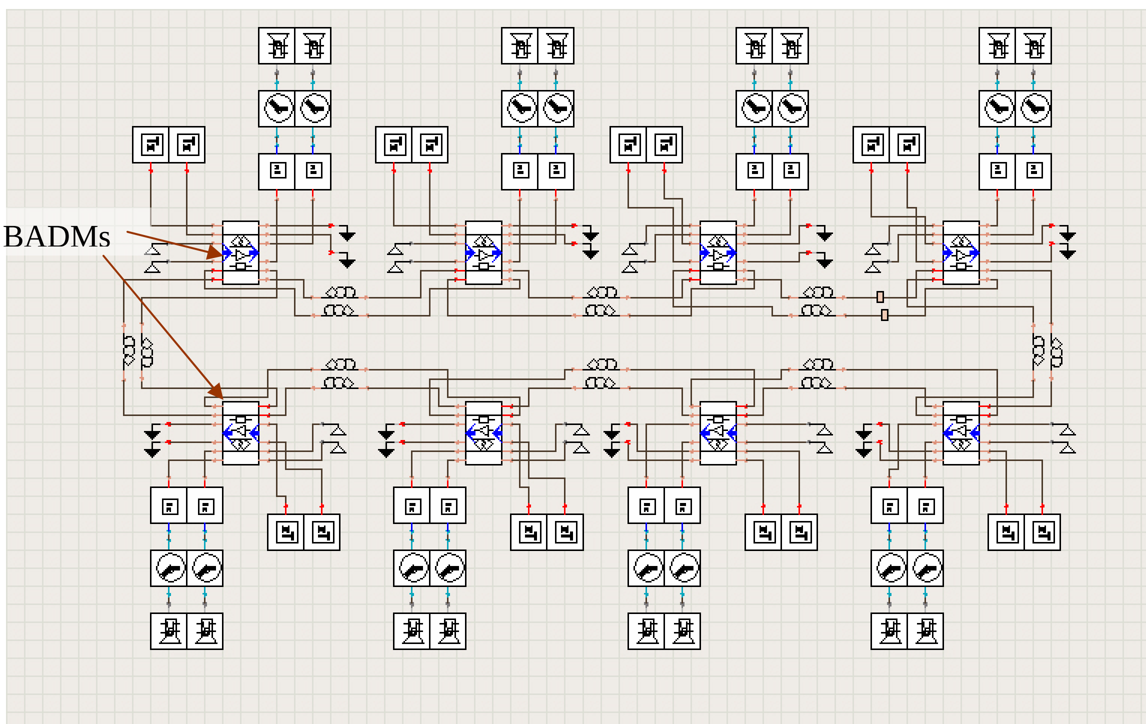


Figure 19: Eight-node fiber ring network simulation

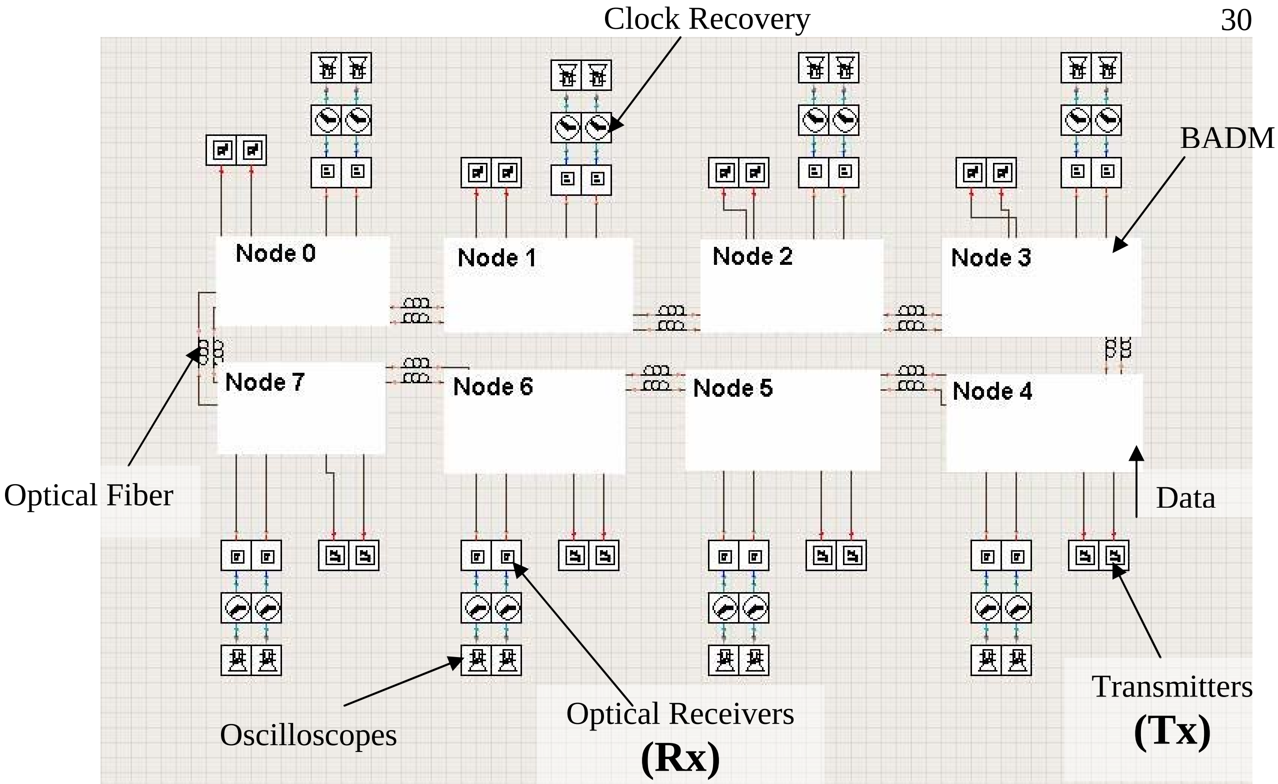


Figure 20: Block diagram of eight-node network simulation

modules. Though somewhat complicated to follow, a resemblance can be seen between Figure 4 and Figure 19 if the outline of each BADM is defined more precisely, as shown in Figure 20.

The original BADM created in the simulation model was based on the circulator/FBG configuration shown in Figure 10. While the simulated ring network operated properly with that model of BADM, it did not accurately model the ring network that was actually built. To model the thin film filter based BADM, the transfer functions associated with each input of the device were used. These were measured during the experiments. In simulation, the transfer functions are implemented with filter modules that specify the predicted spectral response between all the ports of the BADM. These filters are all located inside the box labeled BADM in Figures 19 and 20.

Some other key modules that are used in the simulation are labeled in Figure 20. The

transmitters are the blocks labeled Tx. Each of these transmitters sends out an optical signal with a pseudo-random bit sequence on it. The digital data generated by each transmitter then travels from node to node through the optical fiber modules. To simulate a bidirectional ring network, two unidirectional fiber modules were used in between each set of nodes. The fiber lengths are all chosen to be 1 km.

After being routed by the BADMs, data exiting the network is incident on an optical receiver, labeled as Rx in Figure 20. The optical receiver filters noise from the signal and converts it to an electrical signal. A clock is then extracted from the data to provide a trigger (or timing reference) to an oscilloscope. Without a clock signal, an oscilloscope cannot be synchronized with the data and cannot create an eye diagram.

The first simulation that was run was nearly identical to the test done in the lab for which Figure 14 was generated. In this test, the outputs of Node 0 and Node 1 were displayed using OSAs. The simulation schematic for this test is shown in Figure 21. The modules that look like

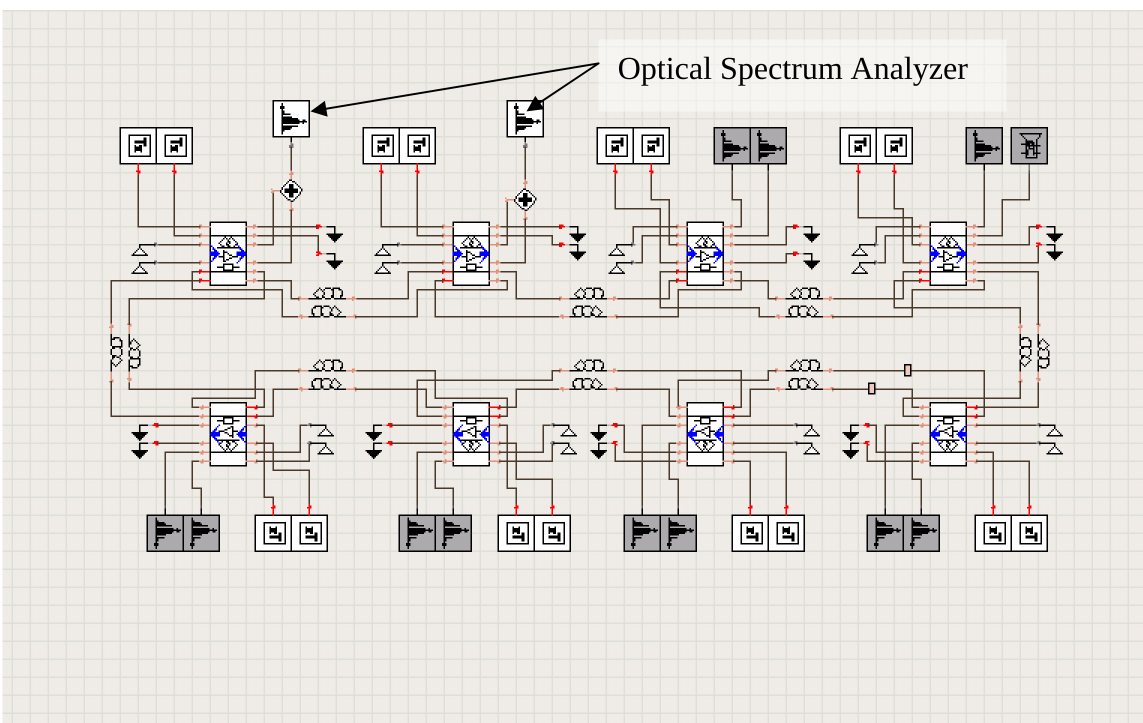


Figure 21: Initial simulation to verify network's operation

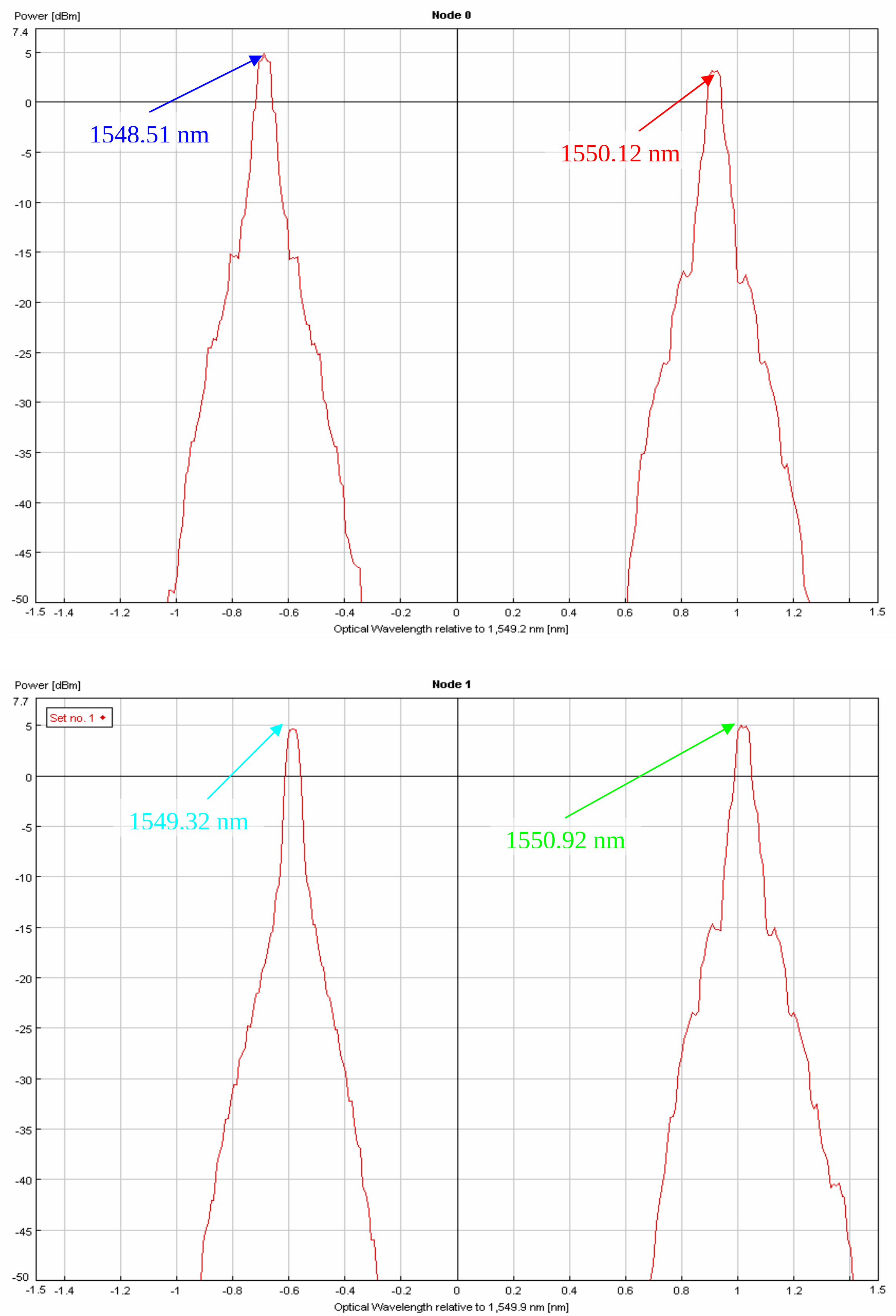


Figure 22: OSA plots for received channels at Nodes 0 and 1

circles with plus signs in them are summing modules, which combine the signals from two wavelength channels onto a single output. Figure 22 shows the two OSA plots that were received at each node. The power levels in these figures are consistent with those from Figure 14, taken during tests of the actual network. Each channel output depends on the attenuation encountered while traveling through multiple BADM devices. Recall that the 1550.12 nm channel received at Node 0 and the 1549.32 nm channel received at Node 1 are slightly more attenuated than the other two channels because they each travel through four BADMs instead of just two.

The accuracy of the simulations is also demonstrated in Figure 23, showing the eye diagram created for a 2.5 Gb/s data transmission. This eye can be compared with the eye in Figure 17, taken during the actual experiment. During simulation, the channel was also sent through a single 50 km fiber, with a received optical power near 50 µW, similar to the lab result.

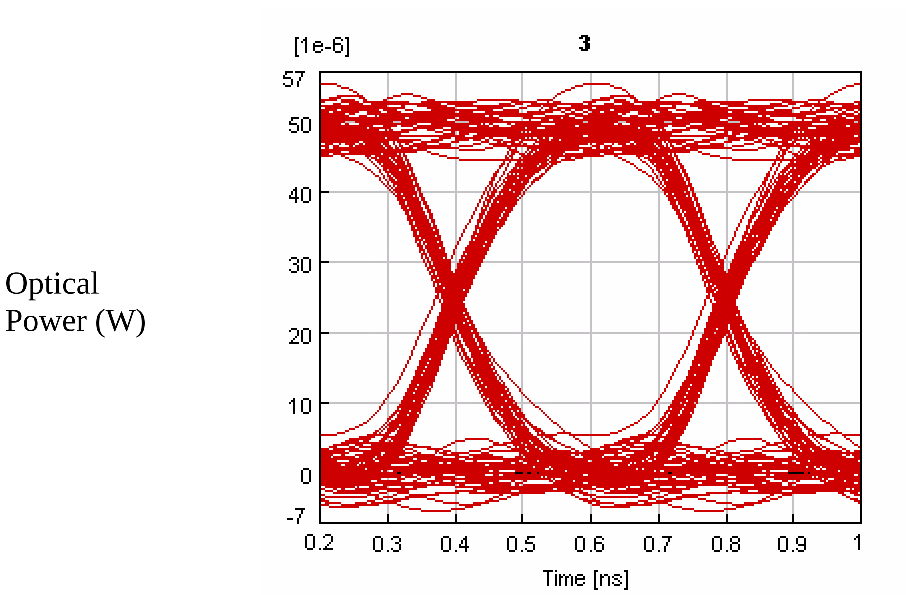


Figure 23: Eye diagram for 2.5 Gb/s of digital data

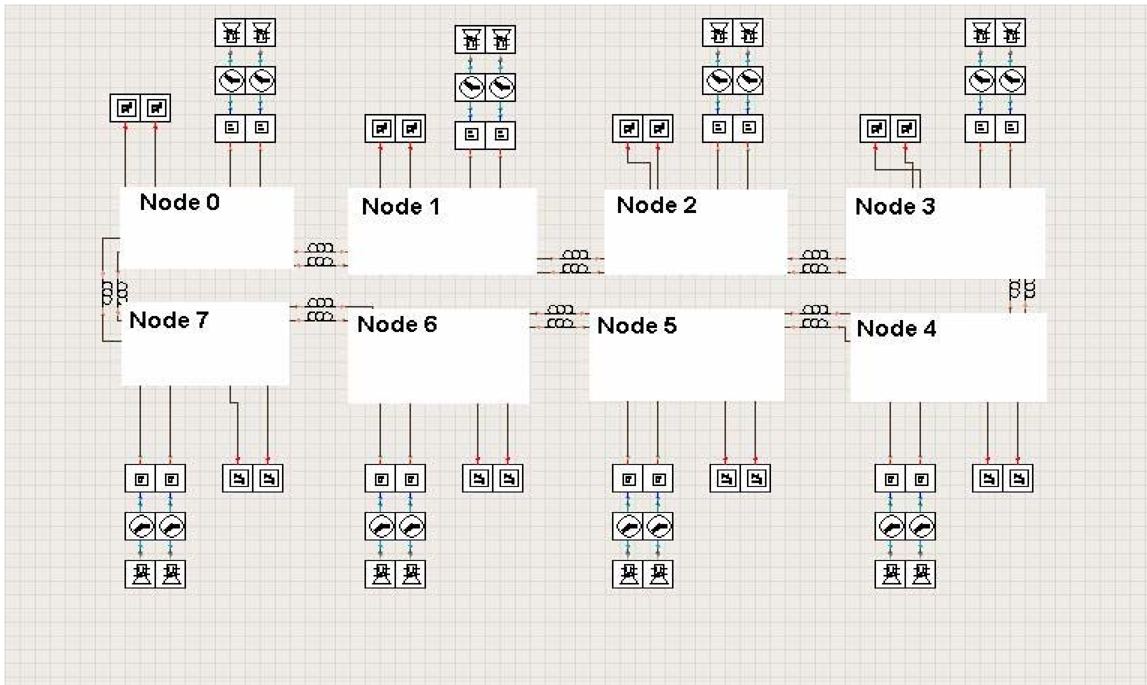


Figure 24: Final simulation setup

The data rate was then raised to 10 Gb/s on all 16 frequency channels. The schematic for this test is shown in Figure 24. When the simulation was run, 16 different oscilloscope plots were displayed. Any degradation of the signal would be seen in an oscilloscope plot. With 50 km of

Optical Power (W)

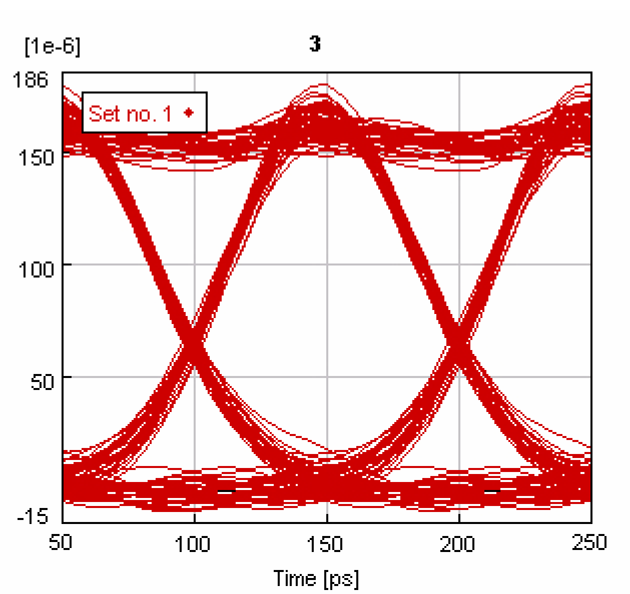


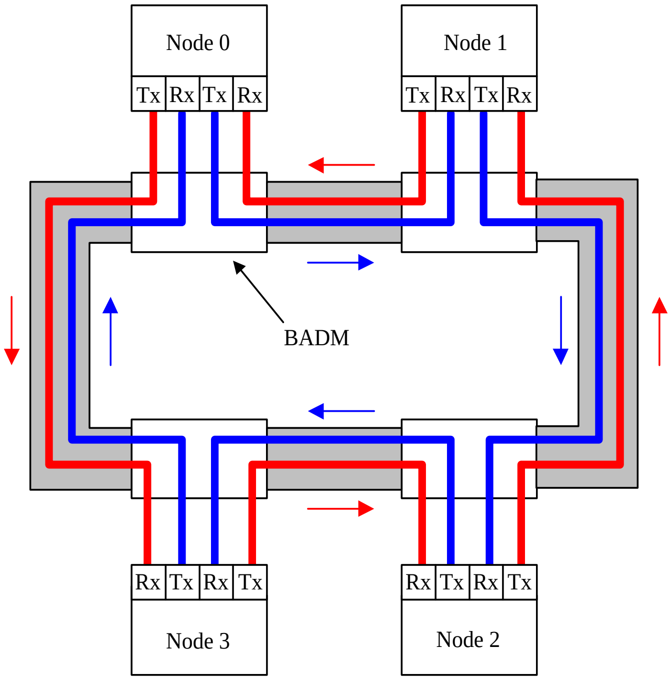
Figure 25: Eye diagram for 10 Gb/s of digital data

fiber attenuation, the eye at 10 Gb/s was somewhat closed. With 25 km of fiber, a clear eye was obtained, as shown in Figure 25. For shorter distances of fiber typical in a LAN, 10 Gb/s transmission would likely be successful. In theory, with 16 transmitters in an eight-node network, 160 Gb/s of data could be transmitted simultaneously.

Network Scalability

In this project, the operation of a bidirectional eight-node WDM fiber ring network was successfully confirmed. Performance at multi-Gb/s data rates was demonstrated. In real world applications, however, not all local area networks have only eight nodes. Thus, an understanding of how such a network would scale in the real world is needed. Three scenarios will be discussed. The first examines how bidirectional fiber ring networks of different sizes can be created. Secondly, the growth of the network by adding one or several nodes at a time can be practically important. Lastly, a way to integrate multiple fiber ring networks will be shown. This section discusses methods to solve these problems. The theory is given in the paper by Karol [2].

The network in Figure 26 illustrates how BADMs can be used to implement a four-node two-wavelength network in a ring topology [3]. While this network does not meet the criteria given in [2] for a perfect shuffle, it demonstrates the flexibility for implementing other topologies with the BADM devices. The connectivity for the network is also shown. In general,



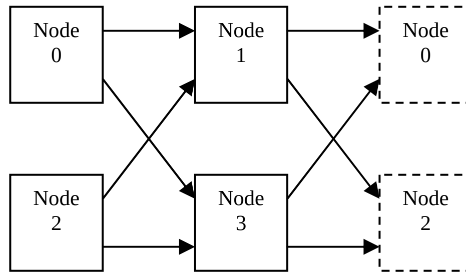


Figure 26: Four-node fiber ring network using four BADMs.

the number of nodes in a perfect shuffle network is somewhat flexible. Scalability of a perfect shuffle network that includes eight or more nodes is defined by the following equation,

$$N = kp^k, \tag{5}$$

where N is the number of nodes, k equals the number of columns that exist in its connectivity diagram, and p equals the number of transmitters and receivers per node. In the eight-node network implemented in this project, p = 2 and k = 2. Figure 27 shows a perfect shuffle with k equal to 3 and p equal to 2. The network supports communication between 24 nodes (3×2^3). The connectivity diagram for the 24-node network is shown in Figure 28. Notice

that the network makes use of six different wavelengths. For any perfect shuffle with a p = 2 and k ≥ 2, the minimum number of required wavelengths, W, needed is based on k and is given by the equation, [2]

$$W = \frac{5 \times 2^k \pm 4}{6} \tag{6}$$

If k is even, the plus sign is used, and if k is odd, the minus sign is used. For the eight-node network k = 2 and W = (5 x 2^2 + 4) / 6 = 4 wavelengths. In the 24 node network k = 3, and W = (5 x 2^3 – 4) / 6 = 6 wavelengths.

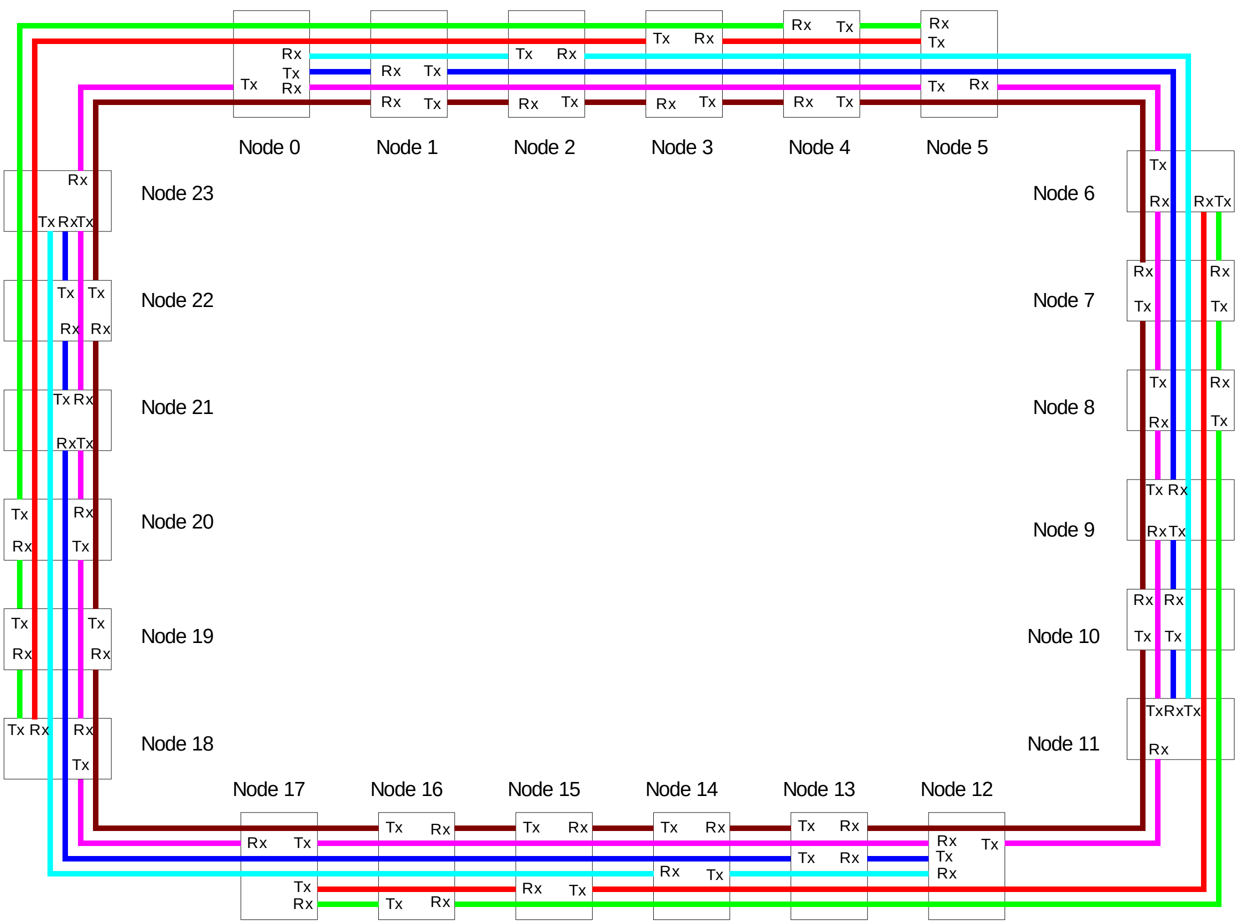


Figure 27: Twenty-four node perfect shuffle.

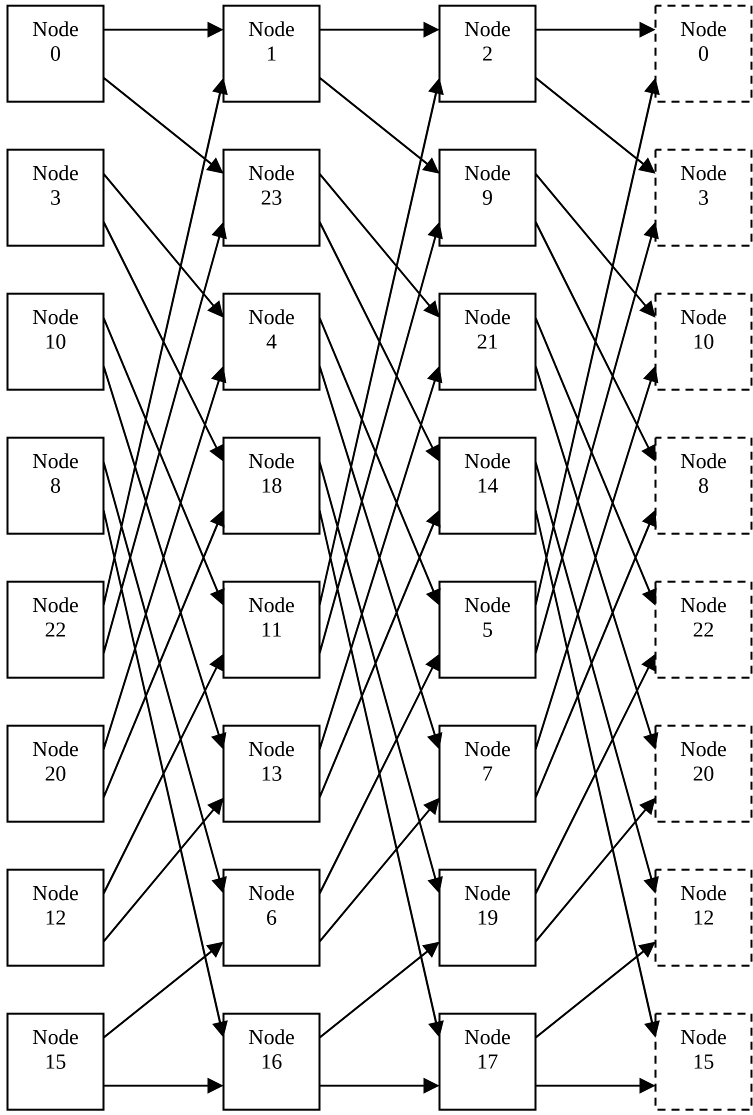


Figure 28: Twenty-four node fiber ring network connectivity.

Scaling a perfect shuffle in this way has its limits, however. Experimentally, each BADM device that was tested had an insertion loss of 1.5 dB between the common ports. Considering that a typical transmitter emits 0 dBm of power and the receiver had a -25 dBm sensitivity, there is a channel power budget of 25 dB. Dividing this budget by the insertion loss of a BADM shows that the maximum number of BADMs a channel may encounter is 16 (16 x 1.5 dB = 24 dB). Thus, a ring network that requires propagation through more than 16 BADMs will not perform

adequately. This also ignores additional losses that occur through the fiber. Note in Figure 27 that there are at most eight BADMs between any two nodes. Hence, the BADMs tested in this project could in theory support a 24-node network. But for k = 4 and N = 64 nodes, the maximum separation between two nodes is greater than 16 [2]. BADMs with lower insertion loss (or a transmitter with more power) would be necessary to build a 64 node ring.

When installing a network, it is unlikely that the number of nodes will remain constant throughout the life of the network, since it is often necessary to expand the network to include more nodes after the initial installment. There are several ways to accomplish this. The first might be to simply install a larger network than is initially required. A fiber ring network with 24 BADMs, but only eight operational, does not result in significant increases in latency. The number of hops is equal on average to the depth of the network, which is four for the 24-node network. This is one of the advantages of the perfect shuffle topology. Until the required number of nodes increases, nodes left vacant would only need the electronics necessary to perform the

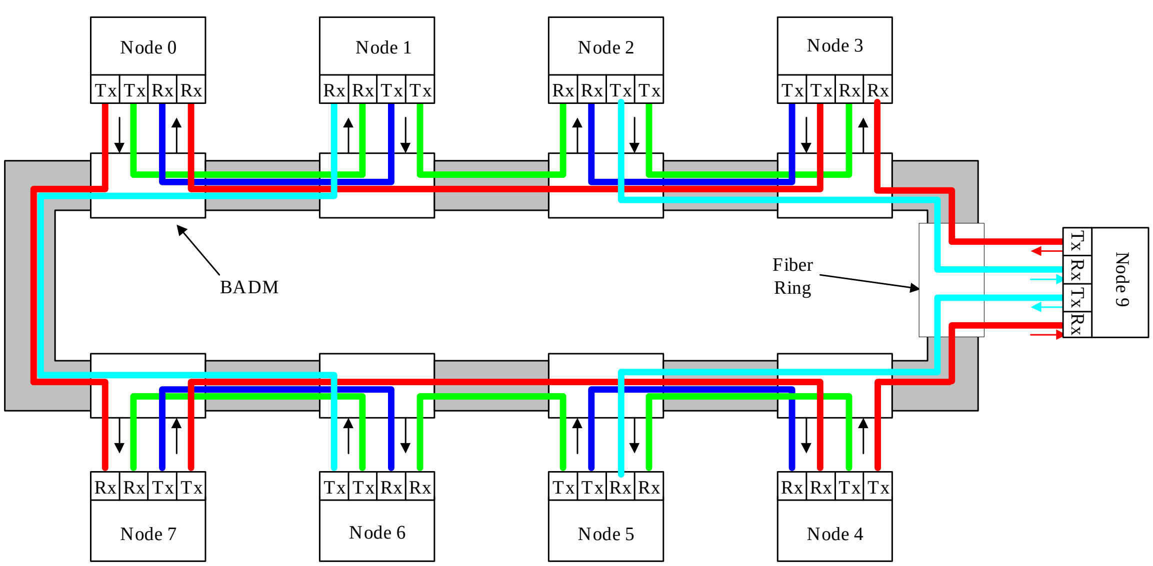


Figure 29: Expanding an eight-node network with a ninth node.

routing function so that the network still functions properly. A second method expands the number of nodes in a pre-existing bidirectional fiber ring network. One way to accommodate this is to add a BADM to the network outside of the already established perfect shuffle. An example of adding a ninth node to the eight-node network is displayed in Figure 29. The introduced BADM mostly allows the original perfect shuffle to be maintained, requiring an additional hop for information on some paths of the network. On the other hand, adding a node in this way adds some flexibility by providing another dimension of routing to the network. If a larger expansion is needed, consider the network in Figure 30, which shows how an eight-node LAN can be connected to a four-node LAN via an intermediary network node. Unlimited expansion is achieved with this method by avoiding power budget limits. Such interconnected rings illustrate a LAN hierarchy that allows for growth into much larger networks.

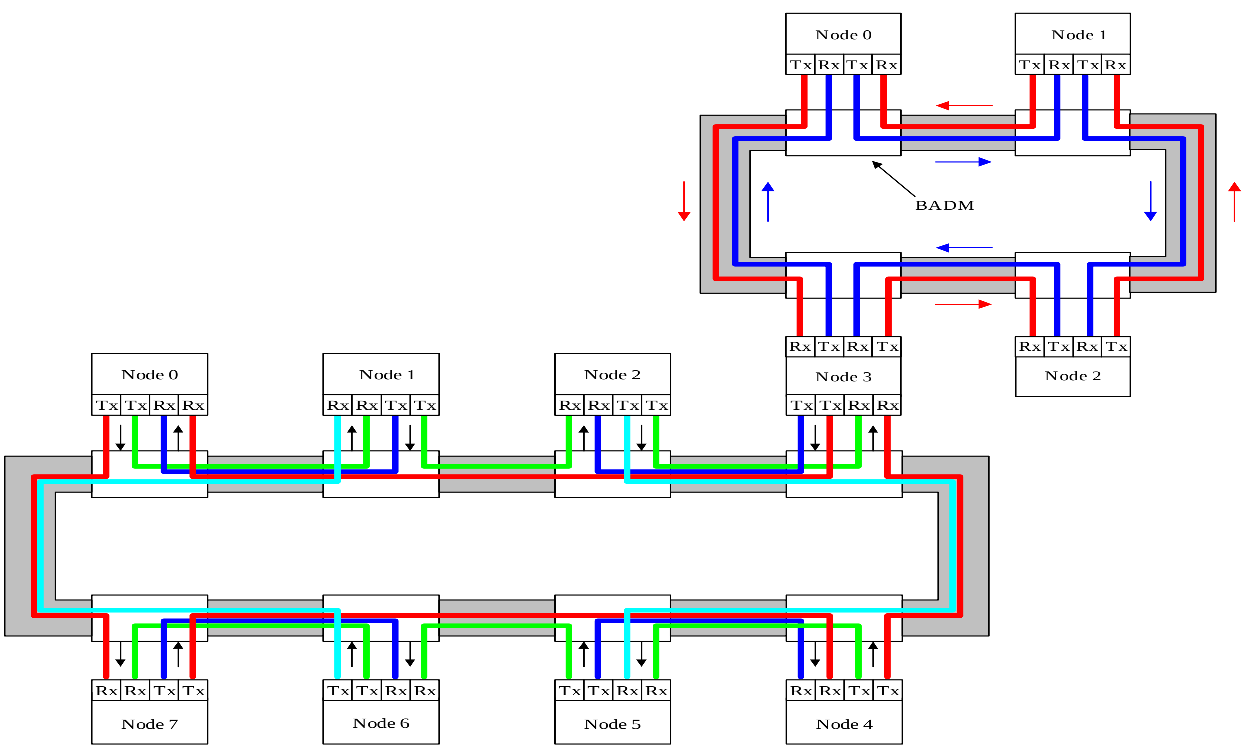


Figure 30: Integrating two ring networks with a common node.

Conclusion

Fiber optic technology is known for its phenomenal bandwidth and low loss characteristic over long distances. The goal of this project was to provide a way to incorporate these characteristics in a local area network environment. Wavelength division multiplexing and perfect shuffle connectivity provided the basis for the physical layer of a network that would accomplish this. Specifically, the physical layer of the eight-node network consisted of a single fiber ring that implemented a perfect shuffle using four wavelengths and eight bidirectional add-drop multiplexers (BADM). The BADMs are new devices, custom-made for this project. They are compact, relatively inexpensive, and responsible for most of the advantages offered by the eight-node network. Such passive all-optical components support the routing of high data rate transmissions on multiple wavelengths in two directions.

The network was built and tested with various data formats. Optical signals carrying digital data at the rate of 2.5 Gb/s and an analog 16-QAM signal propagated through the network simultaneously. The digital signal, after propagating through 50 km of fiber within the network, yielded no errors in three days. This is exceptional considering that, in those three days, nearly 650 trillion bits were transmitted which is the equivalent of 150,000 CD ROMs, or 17,234 DVDs. An SNR of 28 dB was observed with the QAM signal as well. These performance indicators were excellent, despite maximizing the interference and the attenuation through the network.

Extended testing was then done with computer simulation. The network's excellent performance continued, with simulation results demonstrating that 10 Gb/s of digital data on 16 different frequency channels can be transmitted simultaneously through an eight-node network. Excellent performance was observed at 10 Gb/s even with 25 km of fiber within the network.

Based on the analysis of network scalability, with 48 transmitters in a 24-node ring, it may even be possible technologically to support the transmission of 48 channels of 10 Gb/s each, for a maximum aggregate throughput of 480 Gb/s.

Built and tested, the network successfully demonstrated various advantages for a local area network. Among those advantages were higher throughput and the ability to create complex network connectivities, such as the perfect shuffle, with a simple yet flexible fiber topology.

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